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COLORADO STATE UNIV FORT COLLINS DEPT OF CIVIL ENGI--ETC F/6 20/4
AERODYNAMICS - CONTROL OF SURFACE SHEAR STRESS OF FLUCTUATIONS --ETC(U)
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AERODYNAMICS

CONTROL OF SURFACE SHEAR STRESS FLUCTUATIONS
IN TURBULENT BOUNDARY LAYERS

by

V. A. Sandborn

Department of Civil Engineering
Colorado State University

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April 1981

This research was carried out under the Naval Sea Systems Command
General Hydromechanics Research Program Subproject SR 023 01 01,
administered by the David W. Taylor Naval Ship Research and Develop-
ment Center, Contract N00014-80-C-0183.✓

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER CER 80-81-VAS-46	2. GOVT ACCESSION NO. AL-A103-354	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) AERODYNAMICS - CONTROL OF SURFACE SHEAR STRESS OF FLUCTUATIONS IN TURBULENT BOUNDARY LAYERS.		5. TYPE OF REPORT & PERIOD COVERED FINAL
7. AUTHOR(s) V. A. SANDBORN		6. PERFORMING ORG. REPORT NUMBER
9. PERFORMING ORGANIZATION NAME AND ADDRESS Department of Civil Engineering Colorado State University Fort Collins, Colorado 80523		8. CONTRACT OR GRANT NUMBER(s) N00014-80-C-0183
11. CONTROLLING OFFICE NAME AND ADDRESS David W. Taylor Naval Ship R&D Center Attn: Code 1505 Bethesda, Md 20884		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 61153N R023017 SR 023 0101
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) Office of Naval Research 800 N. Quincy Street Arlington, Va., 22217		12. REPORT DATE Apr 1981
		13. NUMBER OF PAGES 32
		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report) N/A		
18. SUPPLEMENTARY NOTES Sponsored by the Naval Sea Systems Command General Hydromechanics Research (GHR) Program administered by David W. Taylor Naval Ship R&D Center, Code 1505, Bethesda, Md 20884		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) GHR Program Boundary Layer Separation Shear Stress Fluctuations Fluctuating Surface Shear Surface Sheer Stress		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) An Experimental study of techniques for modifying the surface shear stress, both mean and fluctuating, in turbulent boundary layers is reported. The surface shear along the test section of a 45.7cm square wind tunnel, with a downstream expansion section, was determined by means of surface-hot-wire- heat-transfer-gauges. Turbulent boundary layers in both zero and adverse pressure gradients were evaluated. The mean and fluctuating surface shear in a zero pressure gradient can be		

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No small size device, which could be mounted in the sublayer, was found that could develop a persistent increase in either the mean or fluctuating surface shear. Small scale vortex generators had no measurable effect on the flow for downstream distances greater than approximately 4 to 5 boundary layer thicknesses. Only the large scale vortex generator, normally used to delay boundary layer separation, produced an increase in surface shear at large distances downstream.

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CONTROL OF SURFACE SHEAR STRESS FLUCTUATIONS IN TURBULENT BOUNDARY LAYERS

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ABSTRACT

an experimental study of techniques for modifying the surface shear stress, both mean and fluctuating, in turbulent boundary layers is reported. The surface shear along the test section of a 45.7cm square wind tunnel, with a downstream expansion section, was determined by means of surface-hot-wire-heat-transfer-gauges. Turbulent boundary layers in both zero and adverse pressure gradients were evaluated.

The mean and fluctuating surface shear in a zero pressure gradient can be effectively reduced by employing a set of closely spaced fins. The fins protruded from the surface up through the sublayer. The fins produced an effective momentum defect for the boundary layer near the surface, which reduced the surface shear fluctuations by as much as 75 percent, two boundary layer thicknesses downstream, and 52 percent 15 boundary layer thicknesses downstream (the limit of the present experiment). The mean surface shear was also reduced by 35 to 25 percent for the same 2 to 15 boundary thicknesses downstream. The fins do not appear to produce a large increase in the thickness of the layer.

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INTRODUCTION

Control of both the mean and fluctuating surface shear in turbulent boundary layers can be of value in a large number of fluid flow problems. Reduction of the mean surface shear in zero pressure gradient flows could reduce the amount of energy required to move ships or aircraft through the fluid. Reduction of the fluctuating surface shear will have a direct effect on the noise generated by the boundary layer. Also the reduction of the fluctuating surface shear in rivers will reduce the movement of sediment.

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At the other extreme, increasing the surface shear will delay the separation of the turbulent boundary layer in an adverse pressure gradient.

Modification of the surface shear in turbulent boundary layers is not a new concept. Snow fences are a direct attempt to reduce the shear, in order to keep the snow from covering passage ways. Blowing and suction are also methods of modifying the boundary layer, which in turn modify the surface shear. Large scale vortex generators are employed to delay turbulent boundary layer separation, which may be viewed as increasing the surface shear in the adverse pressure region.

The present study employed a surface heat transfer gauge as a direct means of evaluating the effect of a number of devices on the surface shear. The gauge can indicate both the mean and fluctuating components of the surface shear. Both zero- and adverse-pressure gradient flow was employed for the study.

EXPERIMENTAL SETUP

The experiments were made in a small, 45.7 x 45.7 cm, open return wind tunnel, figure 1. The test section consisted of a near zero pressure gradient region of 190 cm in length. The turbulent boundary layer was approximately 6.4 cm in thickness, and a momentum thickness Reynolds number of 4050 was developed at the measuring station for a freestream velocity of 10.2 m/sec. The static pressure distribution along the centerline of the test surface is shown in figure 2. For the zero pressure gradient studies a surface-hot-wire was located at $x = 198$ cm. A detailed evaluation of the flow at this location is given by Chien and Sandborn (1981). For the adverse pressure study a surface-hot-wire located at $x = 250$ cm was used to indicate changes in the surface shear. Since the present study was of an exploratory nature, most of the tests were made at a freestream velocity of 10.2 m/sec. Only for one set of fins was the effect of Reynolds number explored.

Surface Shear Measurements. - The surface shear was evaluated from surface heat transfer measurements made with hot wires mounted directly on the surface, Sandborn (1981). Platinum-8%tungsten alloy wire, .001 cm in diameter and approximately 0.13 cm long were mounted directly between copper conductors imbedded in a plastic surface, figure 3. The wires are layed directly on the surface, but are not physically attached except at their ends. The use of buried wires are not desirable, since their frequency response to the surface fluctuations is limited. Film gauges were not used, since their effective length in the flow direction is large. The hot wire sensors were built on the special insert plugs, shown on figure 3. The plastic polyimide surface was employed to reduce the heat transfer into the substrate. The plastic material was also black in color, which greatly facilitates the mounting of the surface wires.

The transfer function between the measured surface heat transfer and the surface shear was obtained from evaluation of the boundary layer velocity profiles measured at the location of the sensor. A number of empirical relations exist for surface shear or skin friction coefficient as a function of the velocity profile-momentum thickness Reynolds number for zero pressure

gradient turbulent boundary layers. Figure 4 is a plot of the local skin friction coefficient, c_f , as a function of momentum thickness Reynolds number. Relations for c_f , reported by Granville (1975), Prandtl (1927), and Bell (1979) are also plotted on figure 4. A second relation obtained by Bell (1927), which includes a second velocity profile parameter, form factor H , is also shown on figure 4. Typical measured values of R_θ and H measured in the present study are plotted on the two parameter relation given by Bell. Between the different c_f relations shown there is roughly a $\pm 3\%$ variation in the values of c_f . At the present time it is doubtful that the accuracy of c_f can be obtained to better than $\pm 3\%$ for the low velocity flows considered.

The large fluctuations of surface shear encountered in the zero pressure gradient turbulent boundary layer, produce a non-linear error in the calibration between the surface-heat transfer and-shear. A special technique outlined by Sandborn (1979) was used to correct the calibration for the non-linear averaging. In order to reduce the calculation time an approximate relation was used to evaluate the surface shear for the measurements behind the different devices. The transfer function between the mean surface shear, $\bar{\tau}_w$, and the output voltage of the hot wire (operating in a constant temperature anemometer circuit) is assumed to be of the form, Sandborn (1972)

$$\bar{\tau}_w = [A(E + e)^2 + B]^3 \quad (1)$$

where E is the hot wire mean voltage output and e is the time dependent voltage perturbation about the mean value. Taking the mean of the left hand side of equation (1) results in terms containing e^2 , e^3 , e^4 , e^5 and e^6 . It is assumed that all of the higher moments of the perturbation voltage appear in terms that are small compared to the e^2 terms. Thus, equation (1) is approximated as

$$\bar{\tau}_w = AE^2(A^2E^4 + 3ABE^2 + 3B^2) + 3Ae^2(2A^2E^4 + 4ABE^2 + B^2) + B^3 \quad (2)$$

For each measured value of E and e^2 a value of $\bar{\tau}_w$ was computed. The values of A and B were determined from the corrected transfer function. The approximation appears to give values of $\bar{\tau}_w$ within $\pm 5\%$ of values obtained by the more complex evaluation reported by Sandborn (1979). Repeat calibrations of the surface hot wire transfer function were found to vary by approximately $\pm 4\%$, so the use of equation (2) does not appear to produce a measurable error. The fact that the hot wire is not extremely sensitive to surface shear (i.e. $\bar{\tau}_w \propto E^6$) helps to reduce the non-linear effects. The measurements are presented as a ratio to the undisturbed shear, which was obtained independently from velocity profile measurements. For each ratio the hot wire measurement with and without the shear modification device in place was used. Thus, it was possible to correct for slight variations in the sensor

sensitivity due to small changes in flow temperature. Some uncertainty may exist in the measurements, due to the presence of local pressure gradients induced by the flow modification devices.

The ratio of the fluctuations with and without the modification devices was computed assuming a local linearization of the transfer function, Sandborn (1972). Since the surface hot wire is not highly sensitive to the surface shear, the error due to local linearization (replacing the transfer function by its local slope) is quite small (see the evaluation of hot wire anemometer errors given by Sandborn (1972)). The main error in evaluating the fluctuations is associated with the accuracy of the transfer function. Individual evaluations of the fluctuating surface shear are uncertain by approximately $\pm 5\%$, although the accuracy of the ratios should not have nearly as high an uncertainty. For the present exploratory study both the mean and fluctuating voltages were measured with long time averaging analog volt meters.

Flow Modification Devices. - A number of devices have been tested as possible ways of increasing or decreasing the mean and fluctuating surface shear. A large number of different size fin sets were tested to determine possible trends toward an optimum geometry. Thin ribbons or plates placed parallel to the surface were employed in the basic study of the fluctuating surface shear. The results for thin plates near the surface are given in the companion report, Chein and Sandborn (1981). Some information on larger, thin plates, placed in the outer region of the boundary layer was obtained in the present study. Cylindrical rods placed both on the surface and at slight distances above the surface was included in the study. A thin airfoil with trailing edge blowing was also evaluated. Flexible strips, and solid and open fences were evaluated as possible devices for increasing the surface fluctuations. A number of different sizes and shapes of vortex generators were also evaluated. Sizes and construction details for the devices are given in Table I.

RESULTS AND DISCUSSION

Zero Pressure Gradient Flow.-(FINS) Of the many devices tested the sets of closely spaced fins and the flexible elements were the most effective in reducing both the mean and fluctuating surface shear for the zero pressure gradient flow. Figure 5 shows typical variations of the mean and fluctuating surface shear ratios obtained by placing the sets of fins at various distances upstream of the surface hot wire sensor. The closely spaced ($S = 0.26\text{cm}$) set of fins produce nearly a 30% reduction in the mean surface shear and a 50% in τ' reduction at a distance of 90cm upstream of the sensor. This upstream distance is equivalent to 14.6 boundary layer thicknesses of the undisturbed flow at the hot wire location. Figure 6 shows measurements for a series of small sized fins. The smaller fins produce a pronounced effect at short distances upstream, but there reduction in the surface shear does not persist for as great a distance as that of the large fins.

The velocity distributions at the measuring station with the $S = 0.26\text{cm}$ spaced fins (figure 1) set at 20cm and 90cm are shown on figure 7. The fins produce a large momentum defect in the boundary layer near the surface. Smoke visualization directly down stream of the fins did not indicate a region of separation, although the very large drop in mean shear directly behind the fins would suggest a near separating condition. Directly behind the fins the surface shear fluctuations are nearly non-existent. The values of the fluctuating shear plotted near $x = 0$ are questionable, as they are approaching the noise level of the anemometer system.

As noted on the insert of figure 5, the alignment of the fins with the mean flow was not critical. A variation of 15 degrees from the mean flow direction produced practically no change in the mean shear value. The insensitivity to slight flow angles should be of great value. It was demonstrated by Chien and Sandborn (1981) that the misalignment of the thin plates had a major effect on the surface shear.

Figure 8 is a review of the information obtained to date on the effect of fin-spacing, width and span. For the present boundary layer, fin spacings of the order of 0.1cm would appear to produce the maximum reduction in both the mean and fluctuating surface shear. For direct drag reduction applications there may be a trade off between the spacing and the form drag of the fins. The width of the fin has not been evaluated sufficiently to make a definite statement on the optimum. Likewise the height of the fins need to be investigated further. The present study has also been limited to finite span of the fin sets. Figure 8c) suggests that the results are not critical for spans equal to or greater than the boundary layer thickness.

The effect of Reynolds number was investigated for the 0.26cm spacing fin set (figure 5). Figure 9 shows the measurements for $Re = 4050$, which were also plotted on figure 5, compared with measurements at $Re = 3080$. The percentage reduction in the mean shear is not as great for the lower Reynolds number flow as for the higher Reynolds number flow. The reduction in the fluctuating shear is approximately the same for both Reynolds numbers.

Zero pressure gradient flow. - (Other devices) A number of devices were investigated, which produced a momentum loss and reduction in both the mean and fluctuating surface shear. As noted previously, the use of thin plates, or ribbons near the surface was investigated in detail and the results are contained in the companion report Chien and Sandborn (1981). A number of other possible thin plate configurations, such as two plates in tandem were also investigated. The different thin plate configurations and the indicated shear are tabulated in Table II. In general the two plates in tandem produce a larger local reduction in the surface shear than a single plate, however, the effect persists for a very short distance downstream. As noted in the report by Chien and Sandborn (1981), the plates block the large fluctuation in surface shear from reaching the surface, but they do not alter the production of the large pulses.

In a private communication with the research group at Illinois Institute of Technology it was pointed out that they were modifying the large scale structure of the boundary layer by the use of thin plates placed in the outer region of the layer. Based on the limited information obtained, a series of single and tandem, thin plates were tested in the outer part of the boundary layer. The results of these tests are also included in Table II. While a reduction in surface shear was noted for the outer region plates, the reduction was much less than that observed for either the plates near the surface or many of the other inner layer devices.

Figure 10 is a summary of tests made with a number of different devices: solid fence, open fence, flexible elements, rods on the surface, rods above the surface, jet blowing airfoil, sublayer vortex generators and a large scale vortex generator. Most of the devices show similar characteristics of a large increase in the mean or fluctuating surface shear directly downstream. In one or two boundary layer thicknesses downstream the mean and fluctuating surface shear drops off to values usually less than the base flow value. By four or five boundary thicknesses, the effect of the device on the surface shear is usually quite small. The most surprising result was that the large fluctuation generators, such as the rods above the surface, actually reduce the surface shear fluctuation once they are one boundary layer thickness upstream. It became evident that generation of fluctuations in the sublayer will not persist for any great length downstream.

The flexible element device (figure 10a) was a series of thin plastic strips glued to the surface and bent so they were vertical for no flow. The strips were 2.6cm high (.4 of boundary layer thickness) and between .1 and .2 wide. They were free to bend backward in the flow. The device was not investigated until late in the study, so only a limited amount of data was obtained. Originally it was assumed that the flexible strips would act as turbulence generators rather than dampers. Obviously the strips are acting more as a compliant surface. The flexible elements should be further investigated as a means of reducing the surface shear.

The small vortex generators, shown on figure 10e), were able to increase the surface shear over short distances only. The devices were designed to produce the high and low velocity jets similar to the sweep-burst phenomenon observed in natural boundary layers. It was thought that the high velocity jets would produce a low pressure, which in turn would pull flow from the outer region of the layer inward. Unfortunately, the effect is not able to generate sufficiently large mixing to persist for more than a few boundary layer thicknesses. It may be worthwhile to investigate the small vortex generators further, and also to consider them in conjunction with the large scale generator.

It was found that the large scale vortex generator had no effect on the local surface shear until it was at least six boundary layer thicknesses upstream.

Adverse pressure gradients. - The pressure gradient for the test surface is shown in figure 2. The adverse pressure gradient region was preceded by a strong favorable pressure gradient. Details of the velocity distribution in the adverse pressure region are given in Appendix A. An intermittent separation was indicated at $x = 266\text{cm}$ and a zero-surface-shear stress occurred at about $x = 273\text{cm}$. In order to evaluate the effect of vortex generators on the surface shear near separation, a surface hot wire sensor at $x = 250\text{cm}$ was employed. Figure 11 shows the indicated change in surface shear produced by a number of vortex generators and deflector plates. The large scale vortex generator mounted far upstream in the zero pressure gradient region produced the largest effect (8%) on the mean surface shear. The large scale vortex generator also increased the surface shear fluctuations by 20 to 36 percent. The small scale vortex generators were unable to increase the surface shear by more than 1 or 2 percent, and they actually decreased the fluctuations. Deflector plates set parallel to the ramp gave roughly the same magnitude of effect as the large vortex generator.

The particular flow studied is perhaps too severe in both the favorable and adverse pressure gradient regions. A flow with milder conditions might be a better test of devices for the delay of separation.

CONCLUDING REMARKS

The present study demonstrates the value of the surface hot wire-shear gauge in evaluating the effect of modification devices. Devices, such as rods, were thought to produce effects that last for long distances downstream. Measurements of the velocity profiles and turbulence would suggest that many boundary layer thicknesses are required for the flow to recover. The present measure of surface shear suggests that the disturbances do not persist at the wall for more than a few lengths.

The major effects of the fins in reducing both the mean and fluctuating surface shear suggest that the lateral or 3-dimensional aspects of the turbulence is important. It was observed that thin ribbons or plates could block the fluctuation from reaching the surface, but in no way do the plates alter the development of the fluctuation downstream. Thus, the fluctuations would appear to be controlled by the lateral effects. At present it is not clear just how the fins (or the flexible elements) damp the large scale surface shear fluctuations.

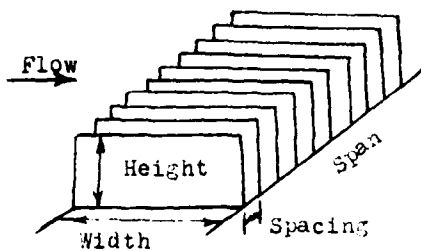
It was assumed that the generation of fluctuations by a number of devices would pose no problem. However, it was not foreseen that turbulence generated near the surface can not persist for long distances. Only the large scale disturbances developed by such devices as large vortex generators that extended across the total boundary layer thickness appear to be able to persist for the large distances required to delay boundary layer separation.

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TABLE I. FLOW CONTROL DEVICES

FINS



0.014 cm thick aluminum sheet used for construction. Each fin is made with a 90 degree bend at bottom of the width of the spacing. Each fin is glued to a 0.014 cm thick sheet. The sheet is in turn glued to the wind tunnel surface.



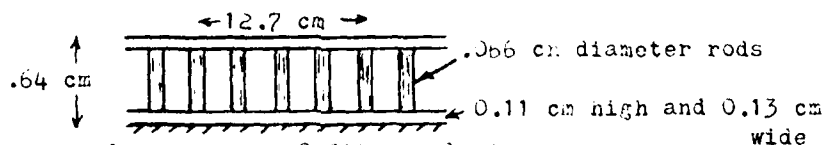
ID	width cm	height cm	spacing cm	span cm
1	3.22	1.75	.264	15.09
2	3.13	1.79	.462	21.07
3	3.190	.765	.13	11.71
4	2.591	.795	.23	19.49
5	2.596	.780	.462	21.07
6	3.15	.765	.13	2.35 to 11.7
7	2.6	.767	.45	
8	.655 to 3.13	.791	.168	3.05
9	2.54	.79	.102	2.54

RODS

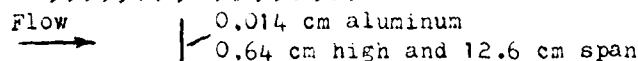
Diameter cm	Length cm	Remarks
.122	33.3	on surface and 2 cm above
.173	33.3	on surface only
.320	33.3	on surface and 0.96 cm above

FENCES

Open



Solid



FLEXIBLE ELEMENTS



BLOWING AIRFOIL

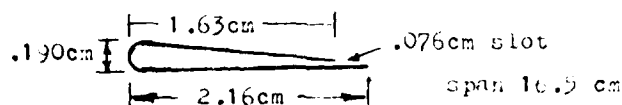
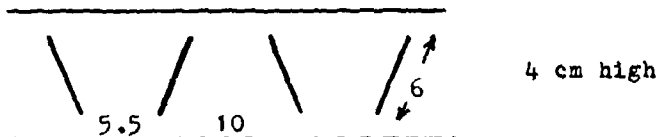


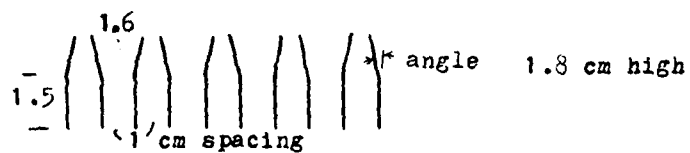
TABLE I. (Concluded) FLOW CONTROL DEVICES

VORTEX GENERATORS

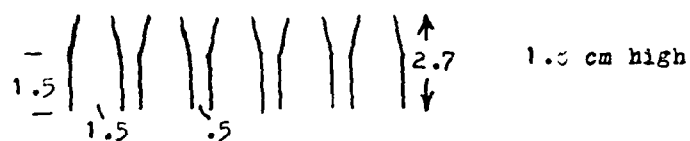
1. Large scale



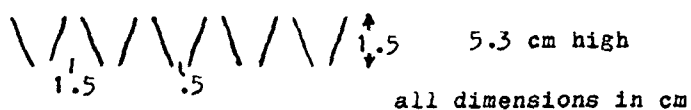
2. Small scale



3. Small scale



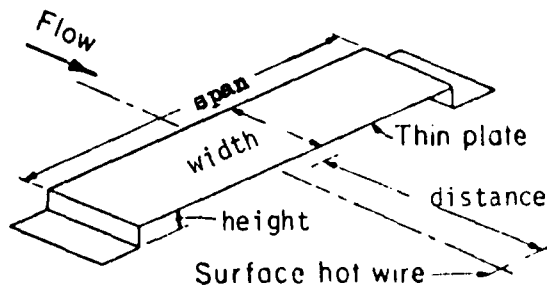
4. Large scale



Flow

all dimensions in cm

TABLE II. THIN PLATE TESTS



1. 5.1 cm wide, 5 cm high, 0.014 cm thick, 20.3 cm span.

Location*	$\tau_w/\tau_{w,0}$	$\tau'_w/\tau'_{w,0}$
3.6	1.00	.934
13.6	1.02	1.03
23.6	1.01	1.03

2. 5.1 cm wide, 2.6 cm high, 0.014 cm thick, 20.3 cm span.

3.6	1.03	1.02
13.6	.984	.953
23.6	1.03	1.06

3. 5.1 cm wide, 0.2 cm high, 0.014 thick, 20.3 cm span.

5.6	.564	.241
15.6	.719	.566

Two plates in tandem

4. 5.1 cm wide, 2.6 cm high, 0.014 cm thick, 20.3 cm span.

Plate 1	Plate 2		
13.6 cm	3.6 cm	1.00	.959
23.6	13.6	.918	.830
33.6	23.6	.943	.868
33.6	13.6	.950	.973
23.6	15.6	.951	.904

Note: plates are together

5. 3 cm wide, 0.014 cm thick, 12.6 cm span.

Location	Height	$\tau_w/\tau_{w,0}$	$\tau'_w/\tau'_{w,0}$
Plate 1 Plate 2	Plate 1 Plate 2		
3.5cm 3.5cm	0.2cm 0.2cm	.493	.052
(Plate 2 only)		.541	.130
11.5 5.5	0.2 0.2	.732	.516
(Plate 2 only)		.627	.290
8.5 3.5	0.1 0.2	.566	.165
(Plate 2 only)		.645	.245
11.5 5.5	0.4 0.2	.538	.246
(Plate 2 only)		.704	.479

* Location of center of plates upstream of sensor.

TABLE II. (Concluded) THIN PLATE TESTS

6. 0.014 cm thick, 12.6 cm span

Location		Height		Width		$\bar{\epsilon}_w/\bar{\epsilon}_{w,0}$	$\kappa'_w/\kappa'_{w,0}$
Plate 1	Plate 2	Plate 1	Plate 2	Plate 1	Plate 2		
7.75cm	3.5cm	0.2cm	0.2cm	1.5cm	3cm	.557	.138
(Plate 2 only)						.621	.218
8.5	2.75	0.2	0.2	3.0	1.5	.590	.246
(Plate 2 only)						.706	.353

Two plates directly above each other

7. 3 cm wide, 0.014 cm thick, 12.6 cm span, plate 1 - 0.4 cm high.
plate 2 - 0.2 cm high

Location cm	$\bar{\epsilon}_w/\bar{\epsilon}_{w,0}$	$\kappa'_w/\kappa'_{w,0}$
-5.5	.543	.779
-4	.792	.711
-1.5	1.04	.465
+3.5	.583	.164
5.5	.616	.247
8.5	.734	.503
11.5	.781	.563
21.5	.863	.789

Three plates directly above each other

8. 3 cm wide, 0.014 cm thick, 12.6 cm span, plate 1 - 0.4 cm high

			plate 2 - 0.4 cm high
3.5	.545	.216	
21.5	.815	.689	plate 3 - 0.2 cm high

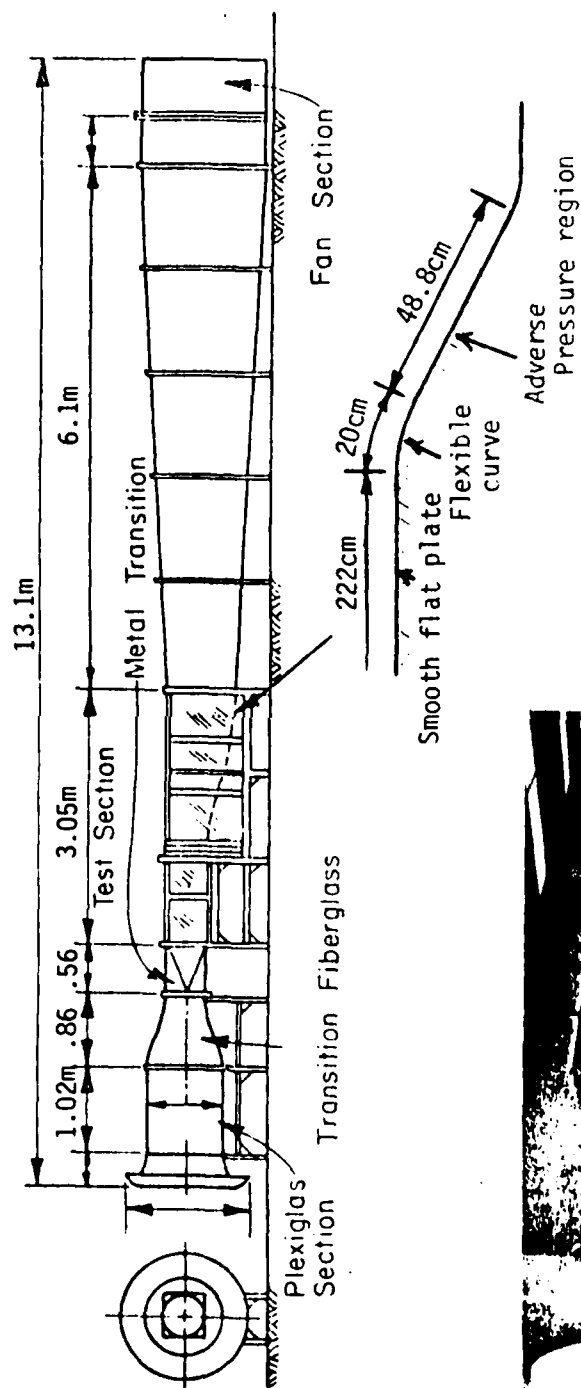


Figure 1. Wind tunnel facilities and steep of the test section.

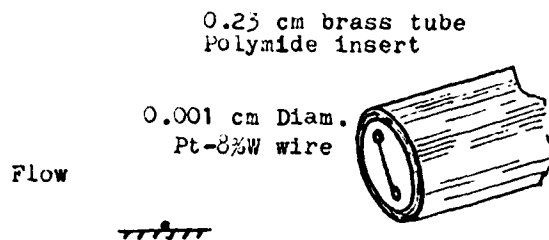


Figure 3. Surface hot wire-heat transfer sensor.

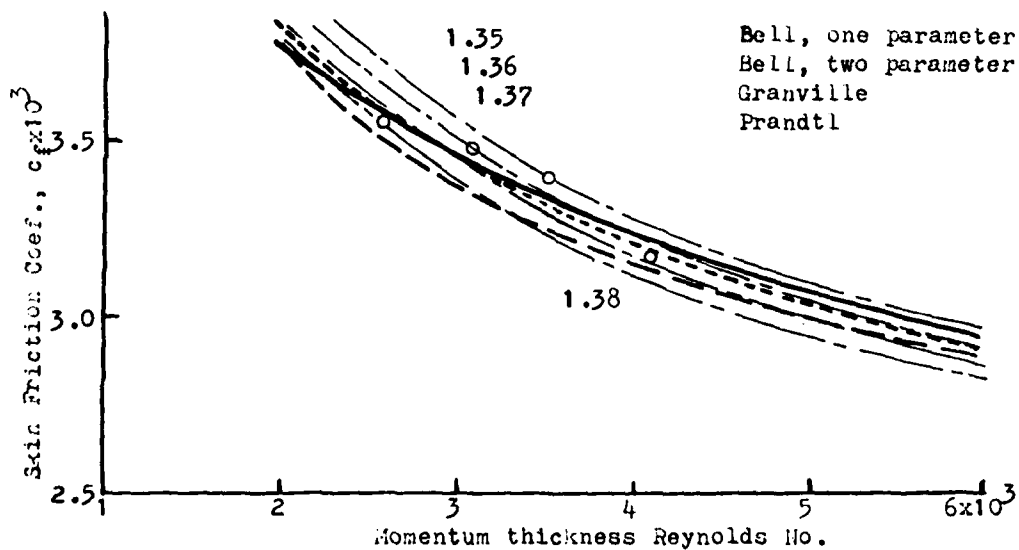


Figure 4.- Local shear stress determination.

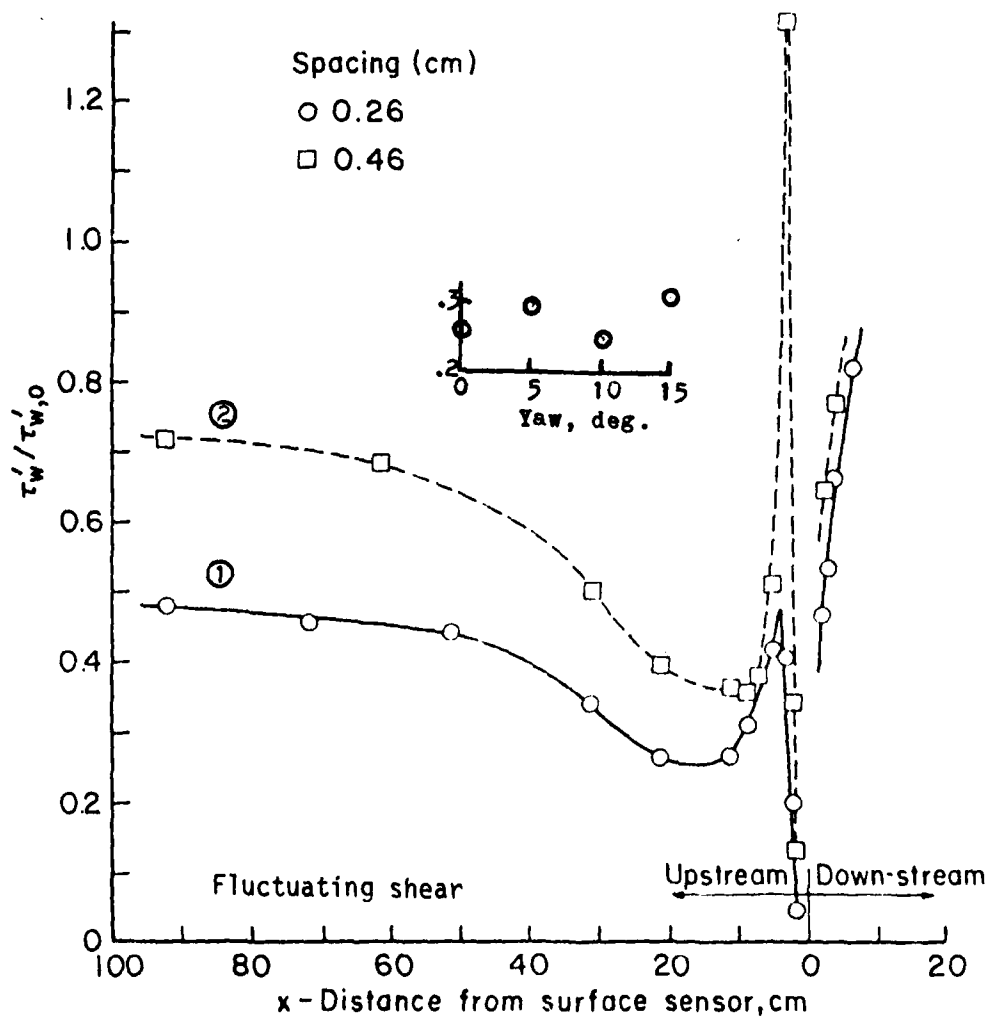
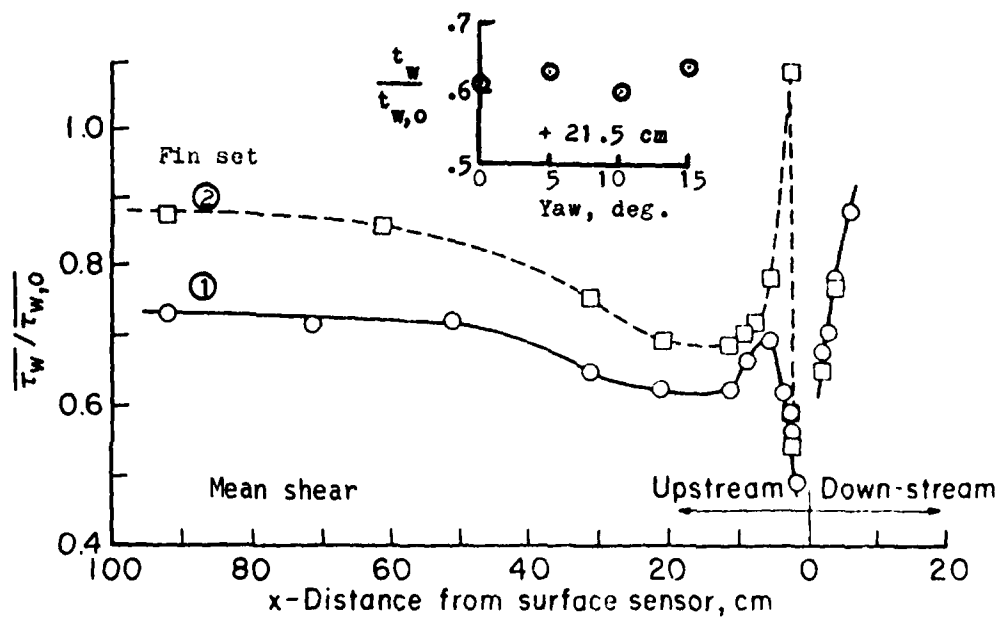


Figure 5.- Variation of the mean and fluctuating surface shear for two sets of fins.

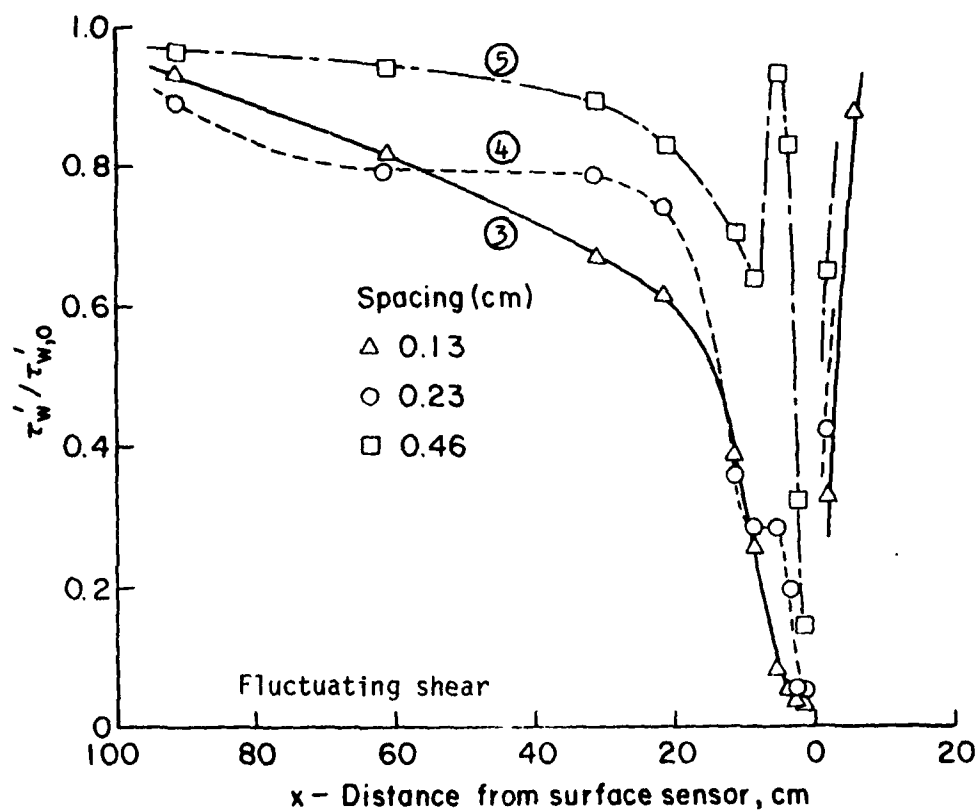
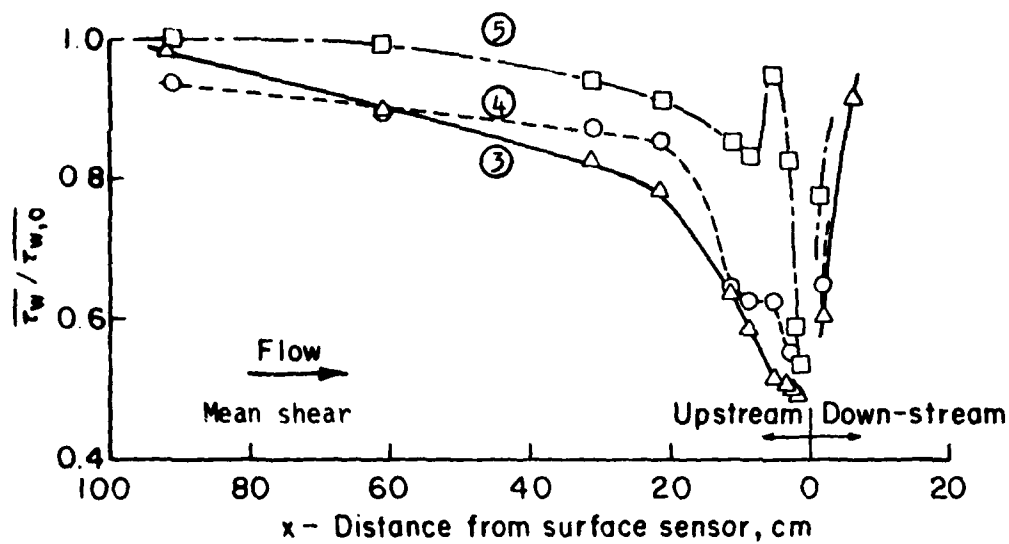


Figure 6.- Effect of small size fins on the mean and fluctuating surface shear.

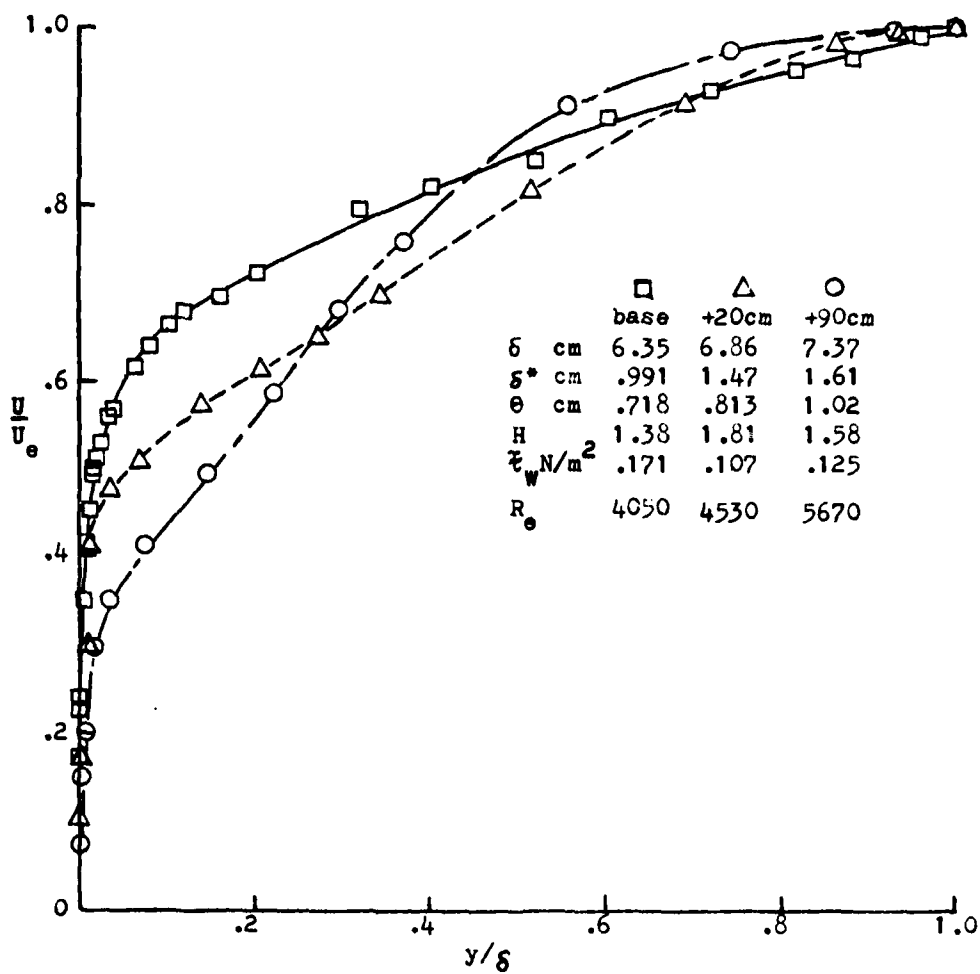
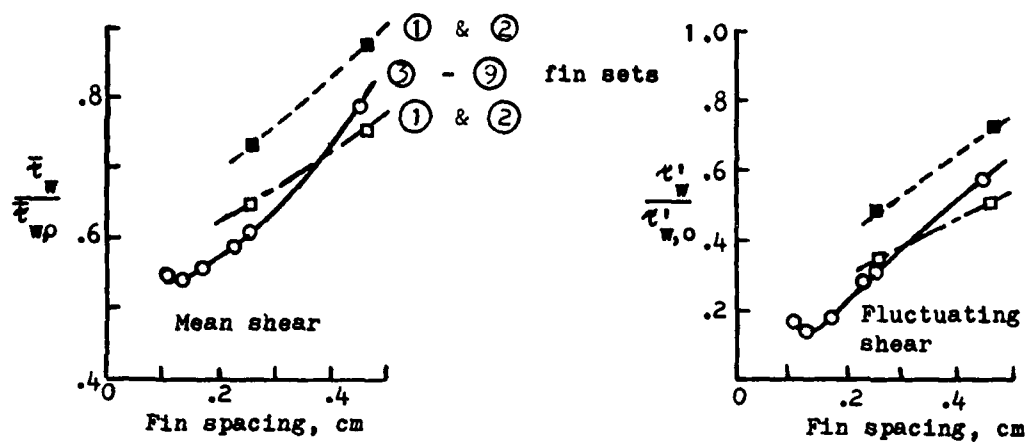
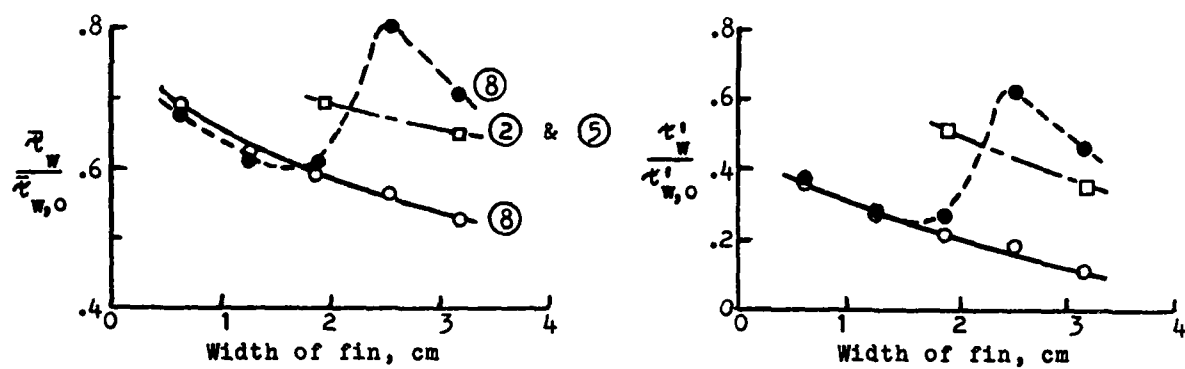


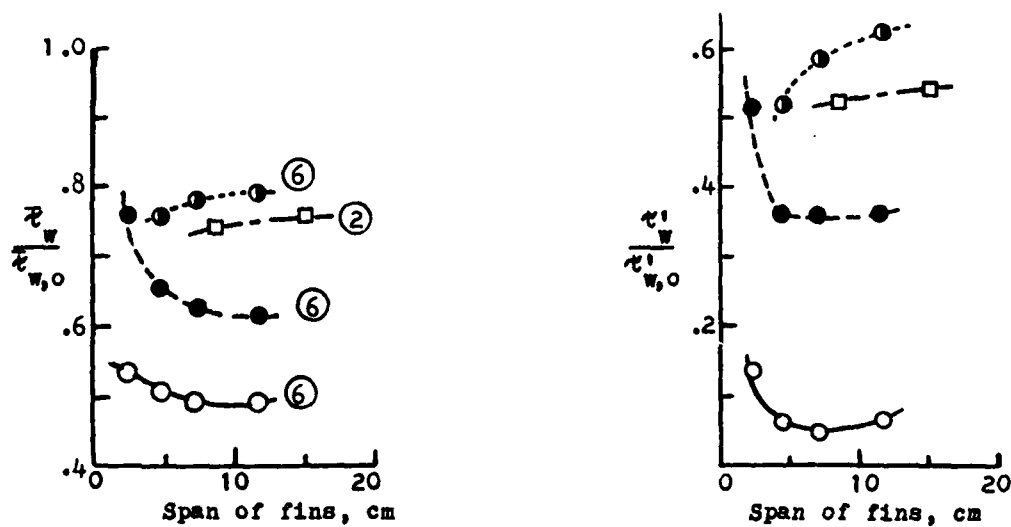
Figure 7.- Variation of the mean velocity distribution downstream of fin set number ①.



a) Effect of spacing.



b) Effect of width.



c) Effect of span.

Figure 8.- Effects of fin geometry on the mean and fluctuating surface shear.

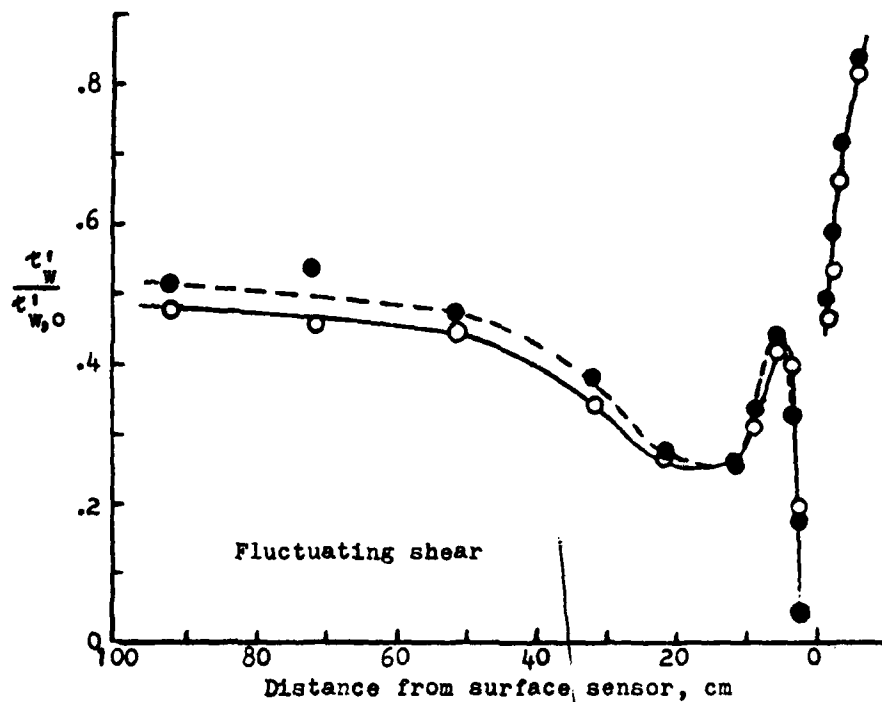
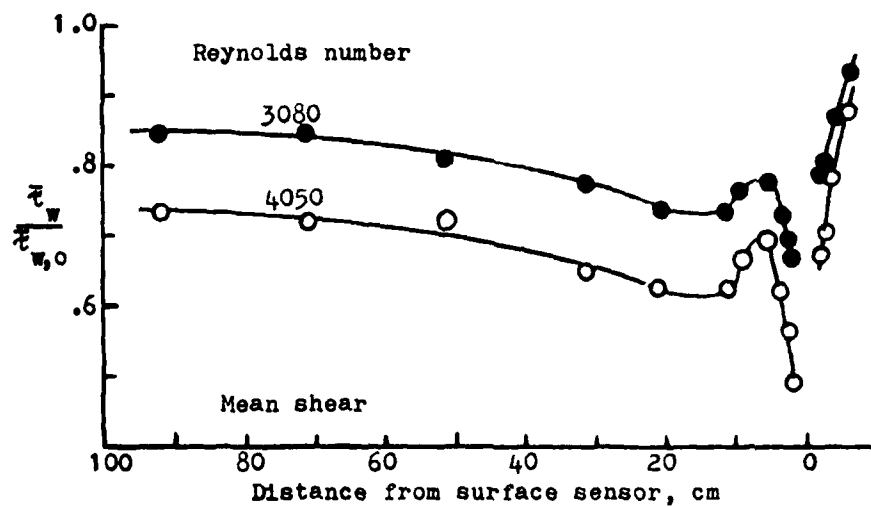
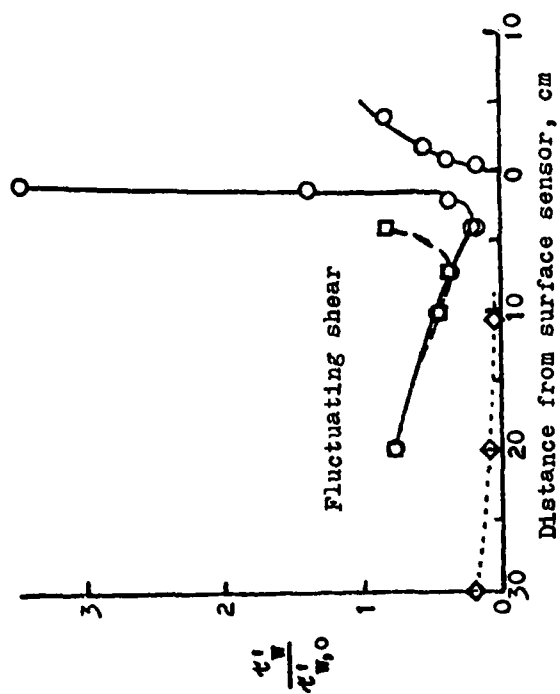
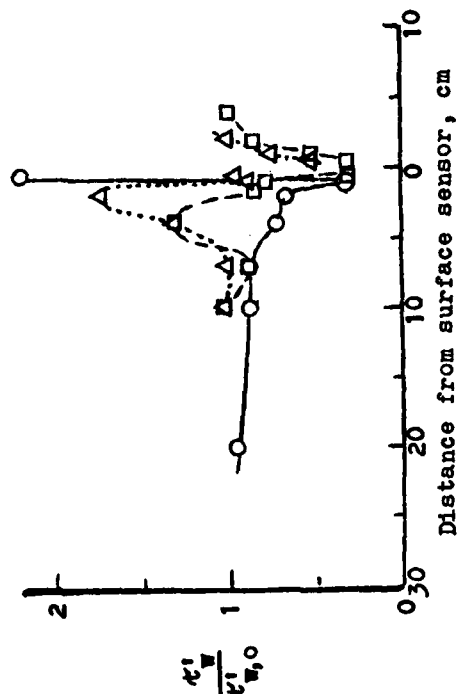


Figure 9.- Reynolds number variation for fin set number ①.

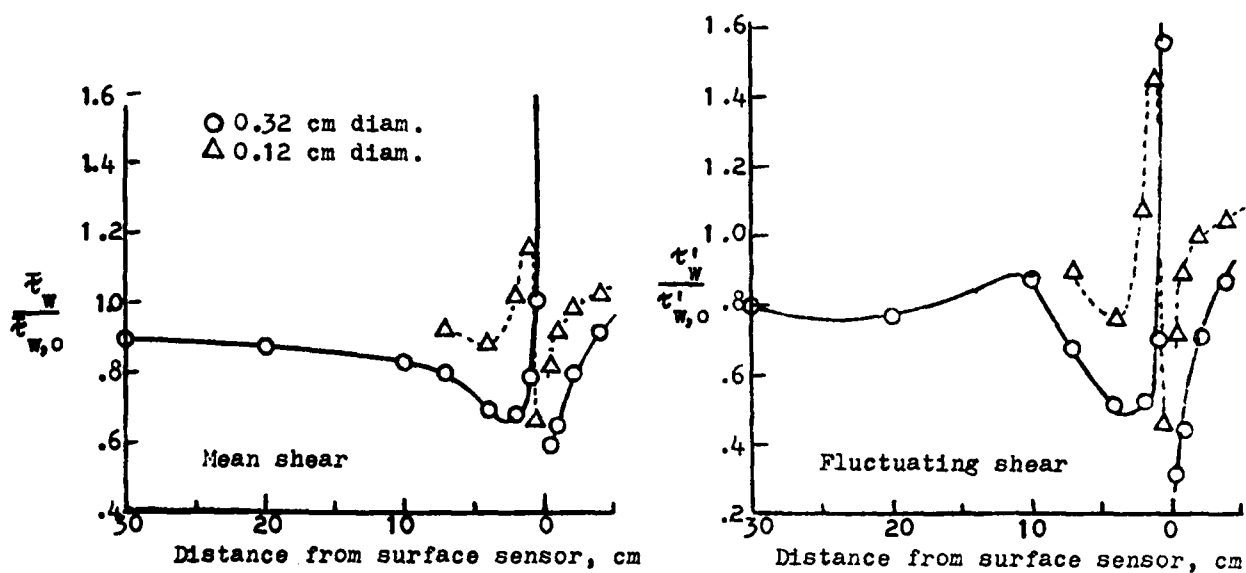


a) Fences and flexible element.

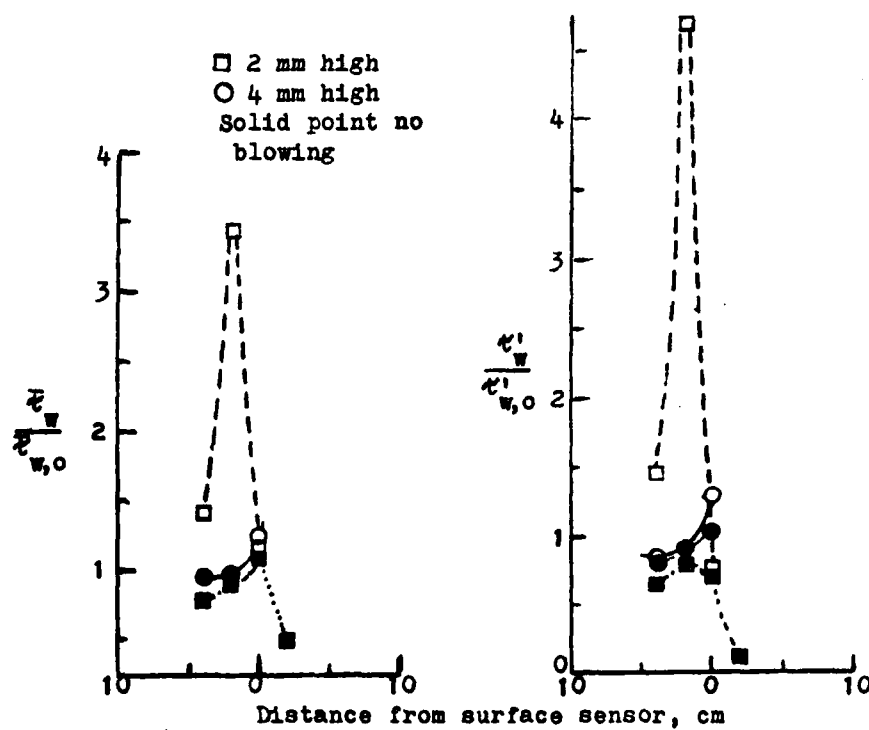


b) Rods on the surface.

Figure 10.-Effect of different flow modification devices on the mean and fluctuating surface shear.

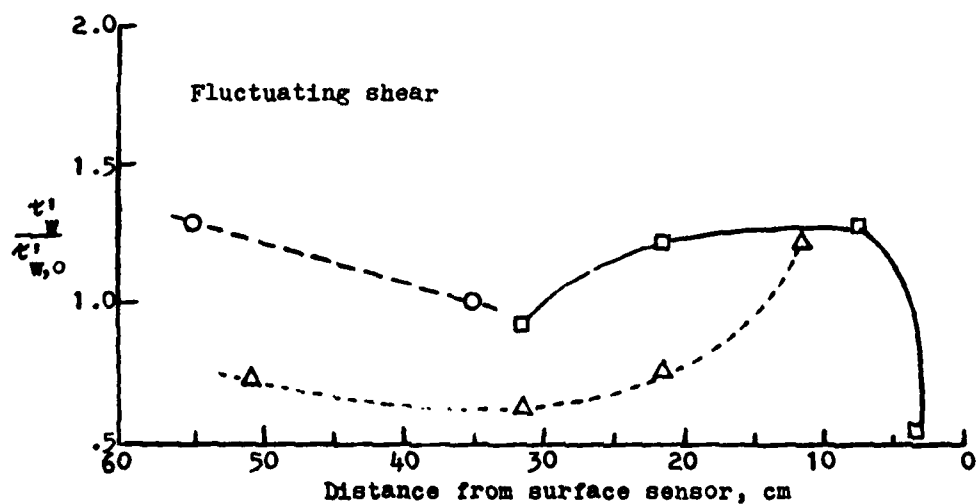
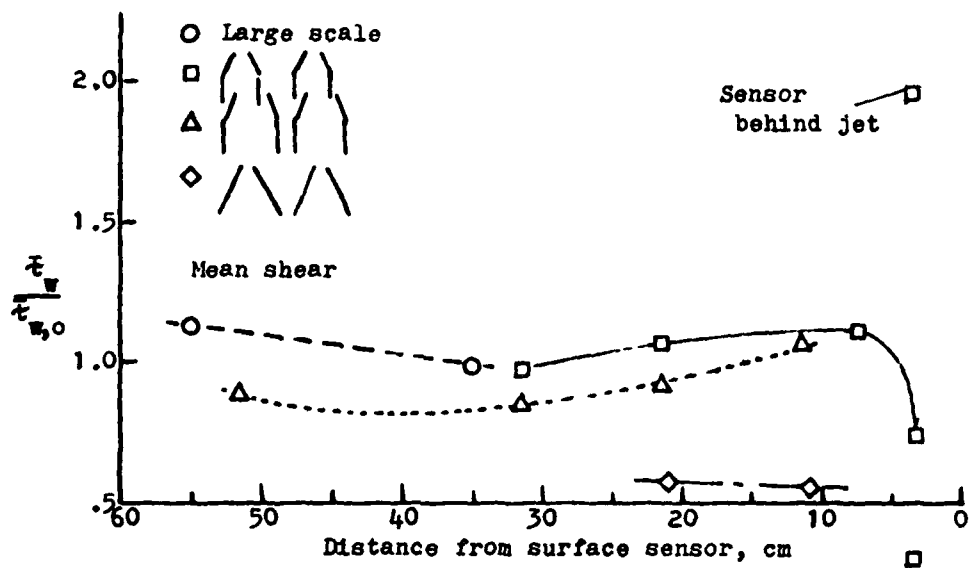


c) Rods above the surface.



d) Blowing jet.

Figure 10.- (continued) Effect of different flow modification devices on the mean and fluctuating surface shear.



e) Vortex generators.

Figure 10.-(Concluded) Effect of different flow modification devices on the mean and fluctuating surface shear.

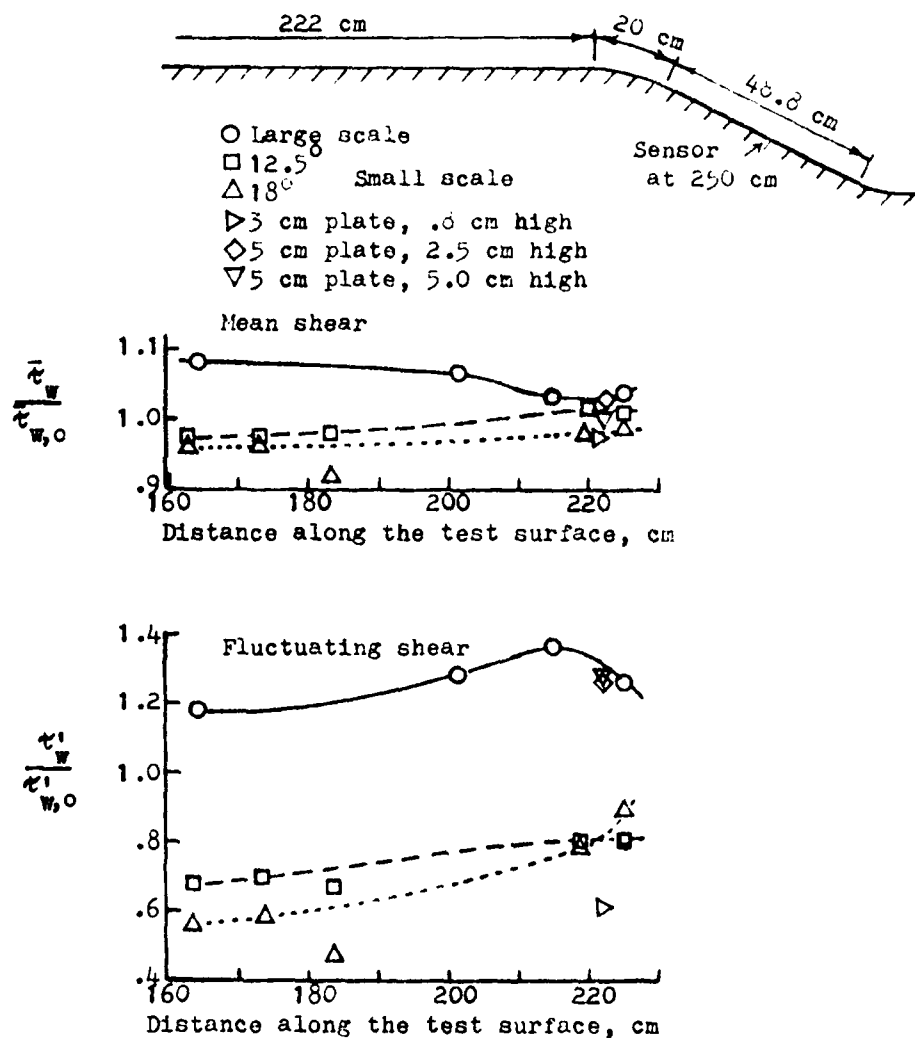


Figure 11.- Effect of vortex generators and deflection plates on the surface shear in adverse pressure gradients.

APPENDIX A

EVALUATION OF THE FLOW IN THE ADVERSE PRESSURE REGION

The wind tunnel test surface was constructed to produce a region of zero pressure gradient flow and then an expansion region of adverse pressure gradient flow sufficient to cause boundary layer separation. The actual set up of the test surface was shown in figure 1. Figure A-1 shows the analog evaluation of the potential flow coordinates for the model as it was set up in the tunnel. Although the potential flow analysis suggested a mild effect of the pressure gradient, the actual measurements indicate a more severe variation in the pressure. Figure 2 shows the measured static pressure along the model for three freestream approach velocities.

The flow was found to accelerate in the region of the initial model curvature and then has a very sharp increase in pressure once the curvature was reached. The sharp change in pressure at the start of the curvature was not desired. However, since the work was done concurrently with the upstream, flat plate measurements, Chien and Sandborn (1981), no attempt was made to re-adjust the model for fear of disturbing the upstream conditions.

The static pressure and mean velocity fields in the region from $s = 247$ cm to 276cm, where visual observations indicated separation was occurring, were determined from a pitot-and a disk type static-probe. Figures A-2 and A-3 show the measured static pressure and velocity variations at fixed heights above the surface. While flow visualization with dust indicated separation was occurring between $s = 260$ and 265cm, the surface static pressure still shows a definite increase. However, the static pressure above the surface at 3cm indicates very little change.

As a first approximation, the boundary layer velocity profiles along the potential coordinates have been evaluated. Figure A-4 shows the computed velocity profiles. The static pressure profiles are shown in figure A-5. The variation of the velocity profile, form factors, and momentum thickness Reynolds number are shown in figure A-6.

Whether the potential coordinate or a coordinate normal to the surface was used had little effect on the parameters for the $s = 248$ and 256cm stations. However, the parameters in the separation region are more sensitive to which coordinate system is used. Figure A-7 shows the boundary layer parameters compared with Sandborn-Kline (1961) separation correlations. The profiles at $s = 266$ cm are close to the "intermittent" separation case. The velocity profiles at $s = 273$ cm for $u = 11.00$ and 8.55 m/sec. fall close to the zero-surface-shear-stress separation case. The estimate of the separation region from flow visualization is consistent with the intermittent separation correlations of Sandborn and Kline. The recently proposed separation criterion in terms of H and R_θ , Sandborn (1979), is compared, figure A-8, with the present data. The values of H and R_θ plotted on figure A-8 correspond to the points where the curves of figure A-7 cross the Sandborn-Kline correlation curve. While the agreement of the present data with the separation criterion shown on fig A-8 are reasonable, further considerations of the proper coordinates for defining the boundary layer profiles are indicated. The separation criterion of Sandborn (1979), is unfortunately based on the two data points shown. These two data points are subject to uncertainties of the same order as the present data.

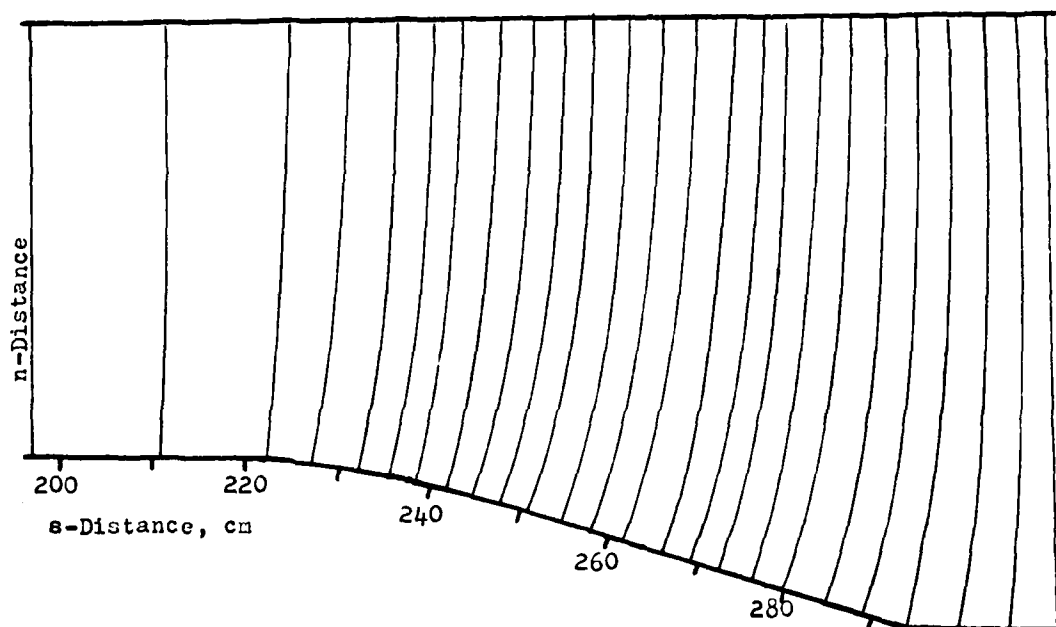


Figure A-1. Wind Tunnel Contour With Equal Potential Lines.

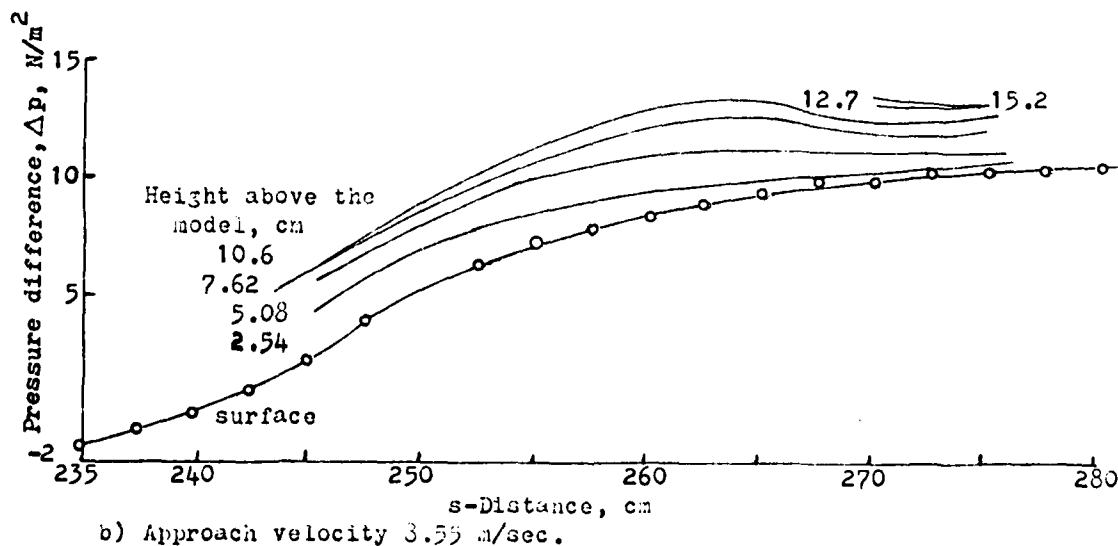
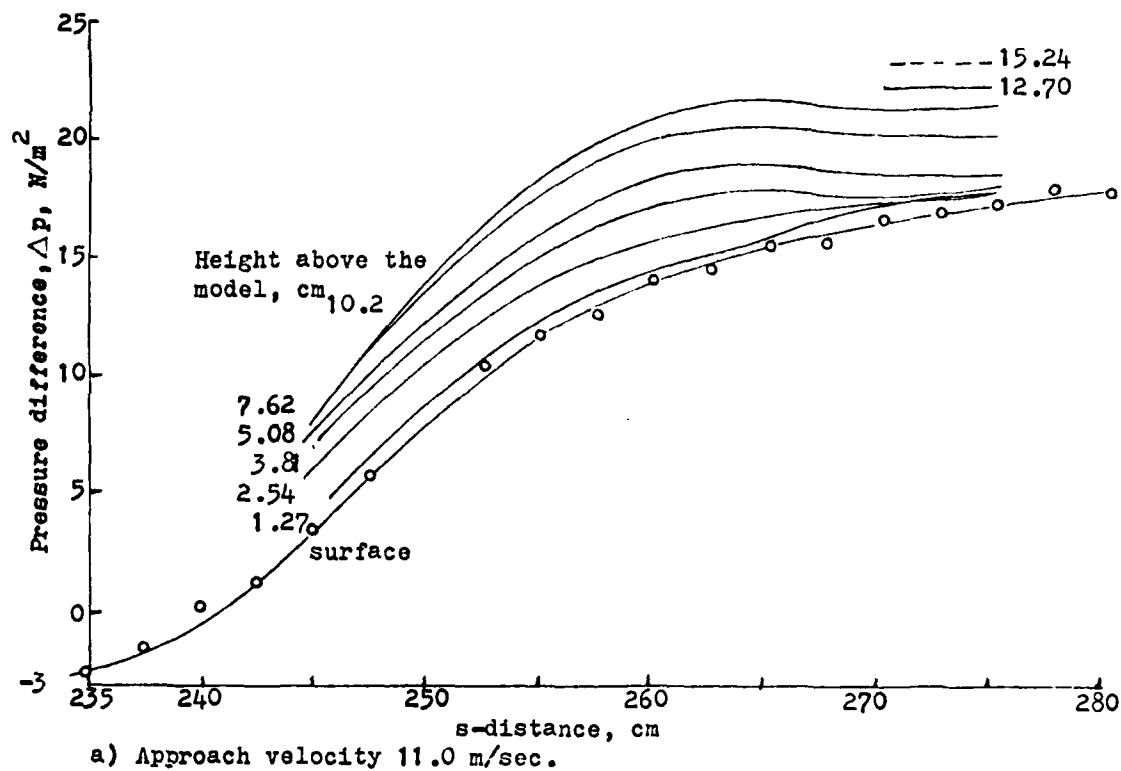
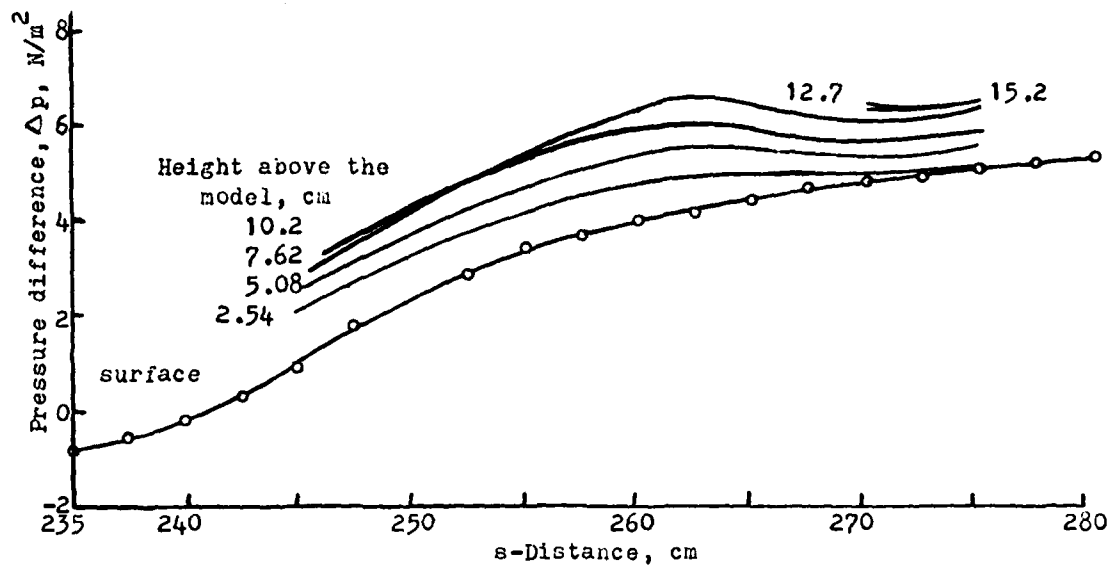
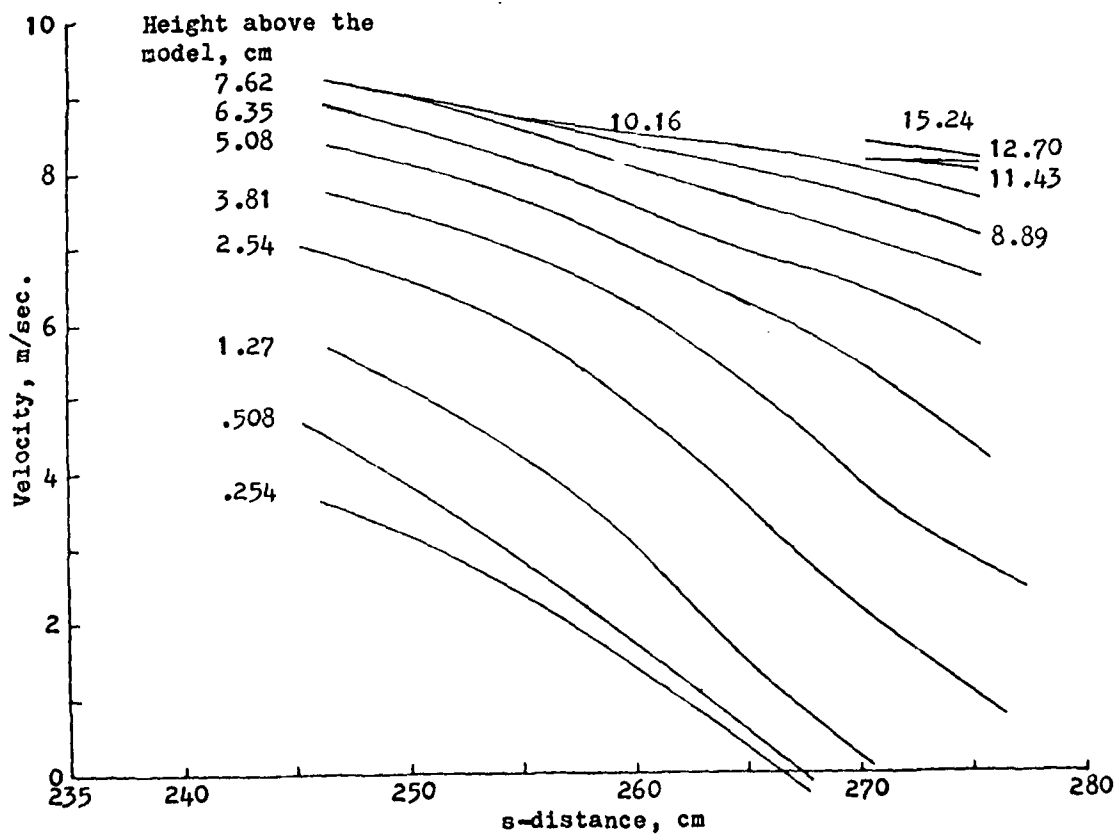


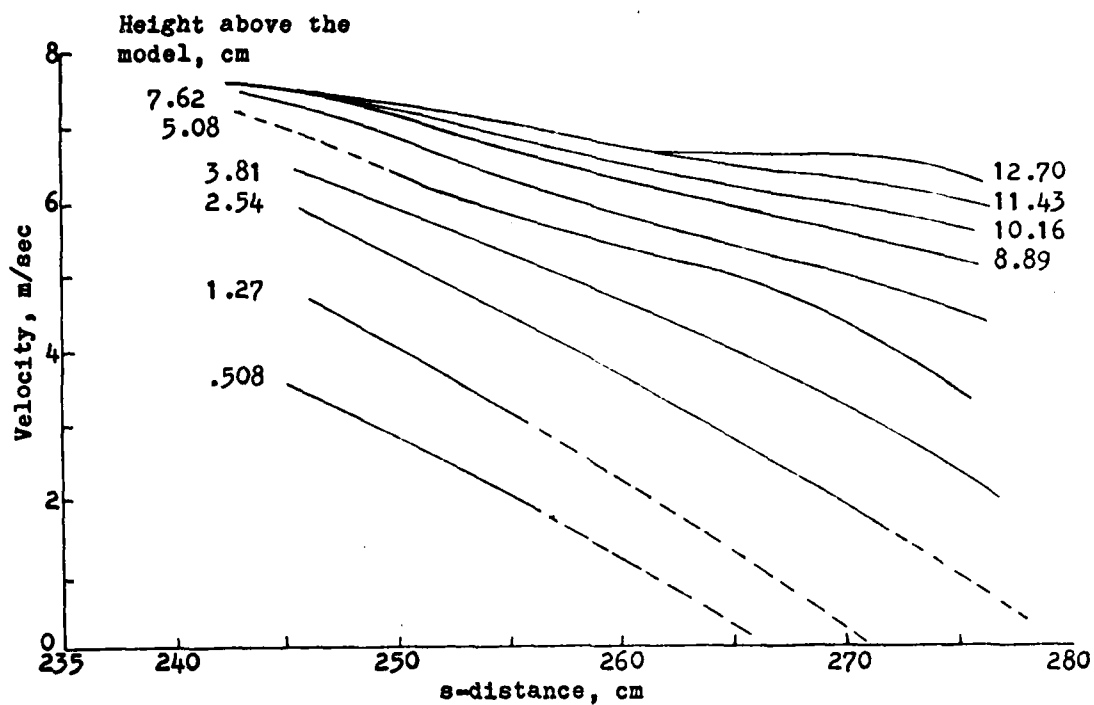
Figure A-2. Static pressure variation above the model surface.



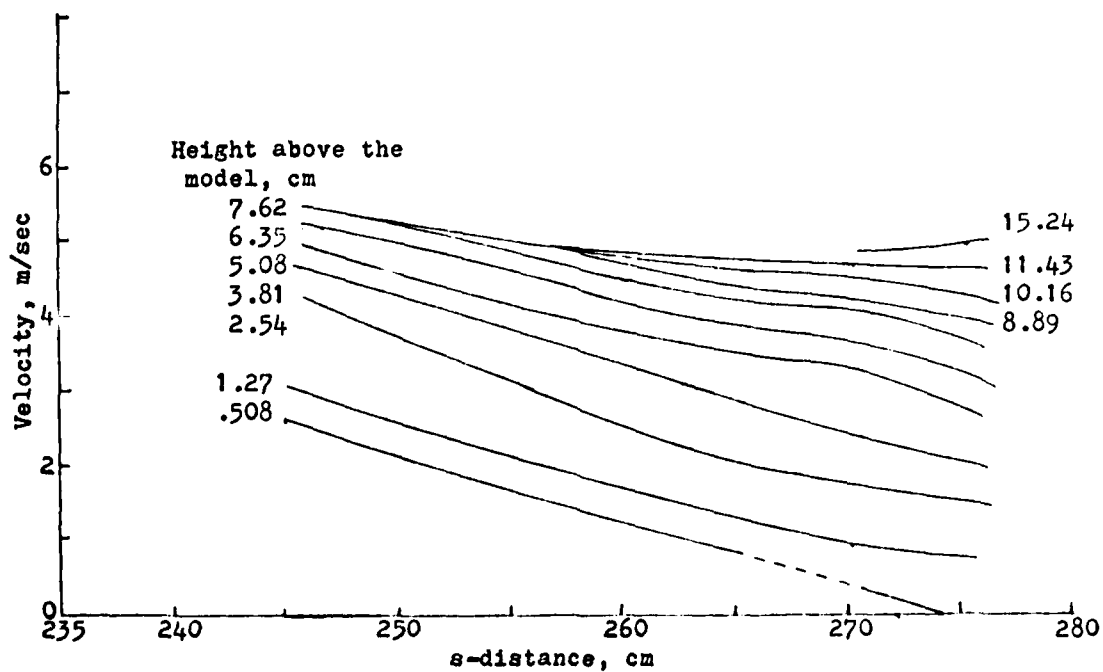
c) Approach velocity 6.30 m/sec.
Figure A-2. (concluded) Static pressure variation above the model surface.



a) Approach velocity 11.0 m/sec.
Figure A-3. Mean velocity variation at fixed heights above the surface.

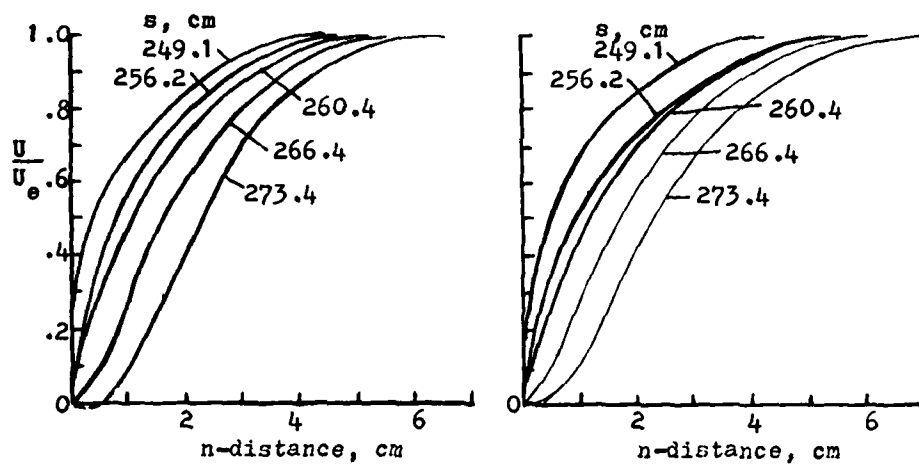


b) Approach velocity 8.55 m/sec.

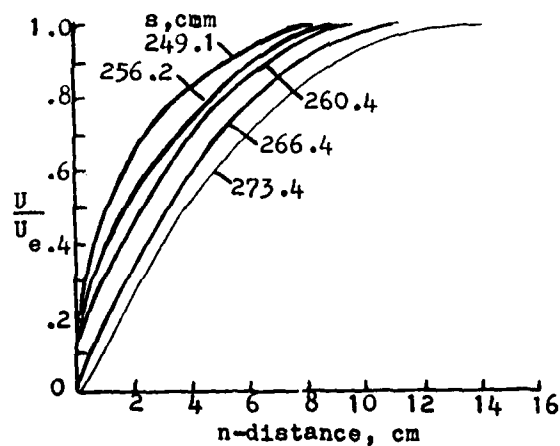


c) Approach velocity 6.30 m/sec.

Figure A-3. (concluded) Mean velocity variation at fixed heights above the surface

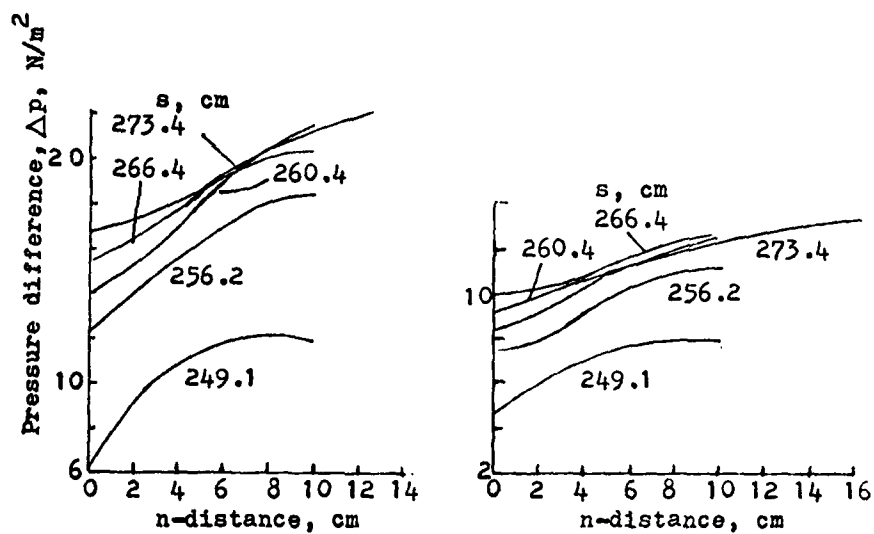


a) Approach velocity 11.0 m/s. b) Approach velocity 8.55 m/s.

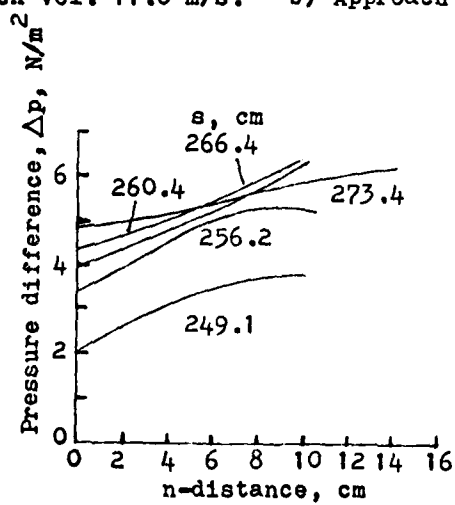


c) Approach velocity 6.30 m/s.

Figure A-4. Velocity distributions along the potential flow coordinates.

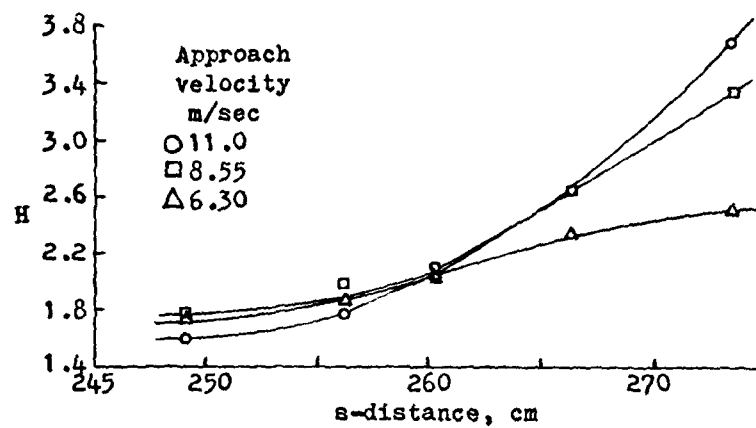


a) Approach vel. 11.0 m/s. b) Approach vel. 8.55 m/s.

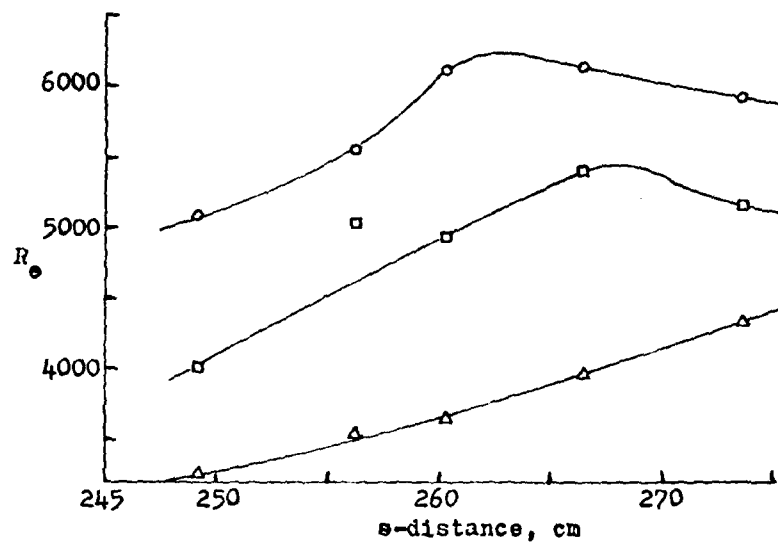


c) Approach vel. 6.30 m/sec.

Figure A-5. Static pressure profiles along the potential flow coordinate.



a) Form factor.



b) Momentum thickness Reynolds number.

Figure A-6. Boundary layer parameters.

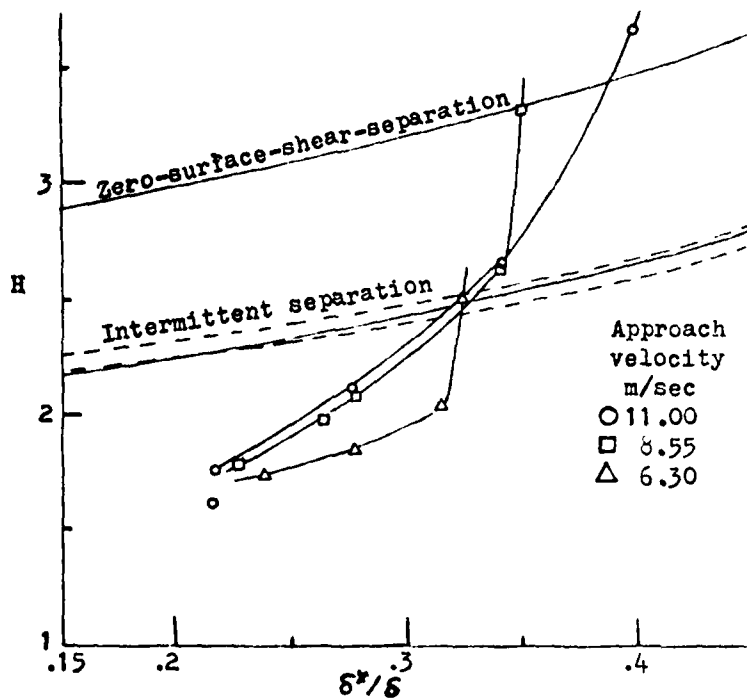


Figure A-7. Comparison of the velocity profile parameters with the Sandborn-Kline separation correlations.

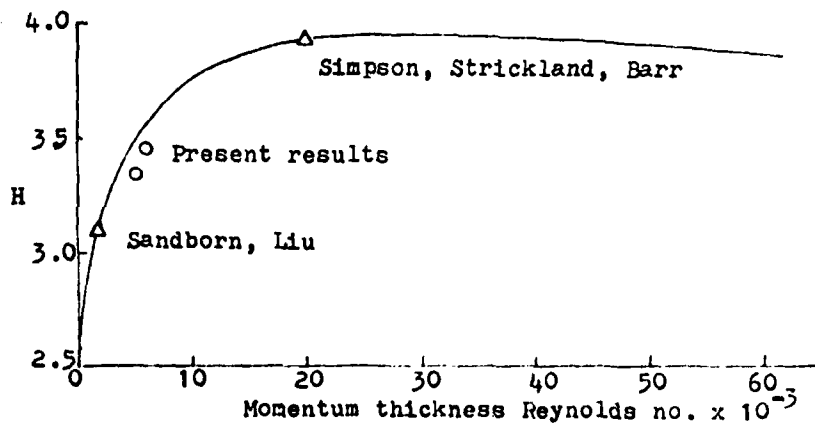


Figure A-8. Comparison of the zero-surface-shear-stress separation criterion of Sandborn (1979) with the measurements.

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